ORDA Calibration Report

ABSTRACT:

The reflectivity accuracy of the WSR-88D depends on the accuracy of the measurements made for parameters intrinsic to the radar equation. This paper shows that the ORDA reflectivity calibration is within 0.5dB, discusses how ORDA casts the radar equation, derives the accuracy of reflectivity, and reports measurements from the radar. The paper is divided into three parts: analysis, variables, and measurements.

This paper assumes knowledge of the radar equation and does not derive it. It also does not derive other basic engineering equations, such as antenna gain. The reader can find these analyses in standard radar texts, and in the "Calibration of the WSR-88D" report dated September 30, 1992 published by the Operational Support Facility.

Analysis

Radar Equation

The basic weather radar equation assumes Gaussian returns with Rayleigh scattering (that is, a large number of small points (less than 0.1λ) in the radiated volume).

The general weather radar equation for Z_e is[i]

$$Z_e = P_R \times R^2 \times \frac{1}{L_P} \times \frac{2^{10} \times \ln(2) \times \lambda^2}{\pi^3 \times P_T \times G^2 \times \theta^2 \times c \times \tau \times |K|^2 \times L}$$

Figure 1, Radar Equation

This equation uses standard metric units and is organized in a "NEXRAD friendly" format. Since Z is normally cast as $\frac{mm^6}{m^3}$, Z_e is converted from m^3 to those units (a factor of 10^{18}).

Table 1 shows the parameters associated with the weather radar equation, and the common units these parameters are displayed in. The radar equation is in standard metric units, so these parameters must be converted to the common units first (i.e. cm for wavelength converted to m for the radar equation).

Table 1, Parameters

Symbol	Name	Units
λ	Wavelength	cm
π	Pi	Unitless
K	Refractivity	Unitless
P_R	Receive Power	mW
P_T	Transmit Power	kW
N	Noise	mW
R	Range	km
L	Losses (except propagation loss) see table 2 for components	Unitless
τ	Pulsewidth	µsec
G	Antenna Gain	Unitless
c	Speed of Light	m/sec
K	Refractivity	Unitless
ln	Natural Logarithm	Unitless
L_P	2 way atmospheric propagation loss	Unitless
g	Receiver Gain	Unitless
θ	Beamwidth	Radians

Table 2, Losses

Symbol	Name	Description	Nominal Value (dB)
L_t	Transmitter	Transmitter Waveguide Loss	2.5
L_r	Receiver	Receiver Waveguide Loss	.63
L_d	Detection	Receiver Detection Loss	Legacy :1.5 ORDA: 0.5
g	Receiver Gain	Receiver gain from Receiver Protector to A/D conversion	Legacy: 55 ORDA: 39

ORDA Version of Radar Equation:

The radar equation cast in logarithmic form for ORDA is:

$$dBZ = 10\log\left(\frac{P_{Rx} - N}{N}\right) + 20\log(R) + ar + dBZ_0$$

P_{Rx} represents the power received from the receiver. This is Signal+Noise. Therefore, ORDA models the signal power as the signal to noise ratio (P_R/N) .

"aR" is the atmospheric loss, where r is range, and a is the atmospheric loss per kilometer (this value is in adaptation data).

dBZ_0[ii] is used as a signal reference to scale reflectivity based on receiver input power. It represents the dBZ of a signal 3dB above the noise (Signal=Noise) at a range of 1km. It subsumes all the non-range dependent constants for the radar equation.

To calculate dBZ_0, we calculate the radar equation for signal power equal to the noise power at 1km. We'll put this into Figure 1, Radar Equation with the following definitions:

$P_R = \left(\frac{2N - N}{N}\right) = 1$ (signal power equal to noise power)

Since P_R has Noise in the denominator, it must be in the numerator somewhere in the radar equation as well
R=1km (since we cast R in terms of km, this will eliminate the range variable)
L_P=1 (since we're using a test signal to calculate dBZ_0, there's no correction for atmospheric gas)
Unit changes: Z conversion to $\frac{mm^6}{m^3}$ is 10^{18}, P_R conversion to mW is 10^{-3} and m^2 conversion to km^2 is 10^6.

Z_0 becomes:

$$Z_0 = \left(\frac{2N - N}{N}\right) \times 1^2 \times \frac{1}{1} \times \frac{2^{10} \times \ln(2) \times \lambda^2}{\pi^3 \times P_T \times G^2 \times \theta^2 \times c \times \tau \times |K|^2 \times L} \times \left(10^{18} \times 10^{-3} \times 10^6\right) \times N$$

Since L is equal to the product of the losses, and our reference point for measurements is the input to the Receiver Protector, L is split up as follows:

$$L = \left(L_t \times L_r \times L_d\right) \times g$$

Now we convert Z_0 to dBZ_0:

$$dBZ_0 = 10\log(P_R) + 20\log(R_0) + aR + 10\log\left(\frac{2^{10} \times \ln(2) \times \lambda^2 \times 10^{18} \times 10^{-3} \times 10^6}{\pi^3 \times P_T \times G^2 \times \theta^2 \times c \times \tau \times |K|^2 \times L_t \times L_r \times L_d} \times \frac{N}{g}\right)$$

For dBZ_0, receive power is at Signal=Noise, so the first term is 0. R_0 is at 1km, so that term is 0. Finally, the test signal used is not traveling through the atmosphere, so aR is 0. This leaves the equation for dBZ_0 as:

$$dBZ_0 = 10\log\left(\frac{2^{10} \times \ln(2) \times \lambda^2 \times 10^{18} \times 10^{-3} \times 10^6}{\pi^3 \times P_T \times G^2 \times \theta^2 \times c \times \tau \times |K|^2 \times L_t \times L_r \times L_d} \times \frac{N}{g}\right)$$

Equation 1, dBZnaught

To measure dBZ_0 in the WSR-88D, we must measure the variable parts of Equation 1. Those are the measurements of Transmitter Power, Noise level, and Receiver Gain. There are other variables that can change (for example, pulse width), but they have very small or zero drift (for example, wavelength). Recasting to reflect this shift, and adding the other conversions (radians to degrees, Kilowatts to watts, centimeters to meters, and μsec to sec), we get:

$$dBZ_0 = 10\log\left(\left(\left(\frac{2^{10}\times\ln(2)}{\pi^3\times c}\times\left(\frac{10^{-3}\times\left(10^3\right)^2\times\left(10^{-2}\right)^2\times10^{18}}{10^3\times\left(\frac{\pi}{180}\right)^2\times10^{-6}}\right)\right)\right)\times\frac{\lambda^2}{G^2\times\theta^2\times\tau\times|K|^2}\times\frac{1}{P_T\times L_t}\times\frac{1}{L_r}\times\frac{N}{L_d\times g}\right)$$

Equation 2, dBZnaught in WSR-88D units

Doing the conversion to dB, we get:

$$dBZ_0 = C + A - P_a - L_{dBr} + I_0$$

Where:

Table 3, Radar Equation Symbols

Symbol	Name	Description	Nominal Value (dB)
C	Constants	Constants from radar equation and unit conversions	163.99
A	Adaptation Data	Constants from adaptation data, nominal 10cm wavelength	-72.43
P_a	Transmit Power	Power radiated into space, in dBKw	26.20
L_{dBr}	Antenna Waveguide Loss	Receive Loss from antenna to receiver input	-.63
I_0	I naught	0dB S/N at receiver input	-113.25

C, A, and L_{dBr} are constants with values that do not change regularly. Therefore, for dBZ_0, we must measure transmitted power and I_0. I_0 is equivalent to MDS of the receiver.

Legacy SYSCAL and dBZ$_0$ Comparison

For legacy, the radar equation is cast as follows:

$$dBZ = 10\log(P_{Rx} - N) + 20\log(R) - 10\log(L_P) + SYSCAL$$

The difference between the legacy and ORDA reflectivity is in how P_{Rx}, return receive power, is handled. In the radar equation, P_R is Signal only. However, in actual radar returns Noise is mixed with Signal and must be accounted for to get an accurate Z_e. In the legacy system computations, P_R = (P_{Rx} - Noise). However, in the ORDA model, P_R/N = (P_{Rx} – Noise)/Noise, the signal to noise ratio is used. This difference is accounted for in the calibration constants (SYSCAL for the legacy model & dBZ_0 for the ORDA model).

$$SYSCAL = 10\log\left(\frac{2^{10}\times\ln(2)\times\lambda^2\times10^{18}\times10^6\times10^{-3}}{\pi^3\times P_T\times G^2\times\theta^2\times c\times\tau\times|K|^2\times L_t\times L_r\times L_d}\times\frac{1}{a^2 g}\right)$$

Figure 2, SYSCAL

$$dBZ_0 = 10\log\left(\left(\frac{2^{10}\times\ln(2)}{\pi^3\times c}\times\left(\frac{10^{-3}\times\left(10^3\right)^2\times\left(10^{-2}\right)^2\times10^{18}}{10^3\times\left(\frac{\pi}{180}\right)^2\times10^{-6}}\right)\right)\times\frac{\lambda^2}{G^2\times\theta^2\times\tau\times|K|^2}\times\frac{1}{P_T\times L_t}\times\frac{1}{L_r}\times\frac{N}{L_d\times g}\right)$$

Equation 2 shows the equation for dBZ_0. SYSCAL and dBZ_0 are used for analogous processes, to correct receive power for all the constants. The difference between legacy and ORDA calibration constants is in the final term. DBZ_0 does not have the a^2 term because the I and Q values we receive from the digital receiver are in voltage, not A/D bits. N is not in SYSCAL since the receive power is modeled as signal only. Note that g is different for legacy and ORDA due to the difference in paths (ORDA does not have the IF or analog components).

Table 3 shows the calculations of SYSCAL and dBZ_0 using typical values for various components. Numerator values are above the heavy line (at Noise value), and denominator values are below. In dB, this changes the sign. The column "Radar Equation Value" shows the number needed for the radar equation. This takes into account where we need exponentiation of a value (for example, the radar equation uses the wavelength (λ) squared, and the Radar Equation Value column is the square of the value column). Refer to the Radar Equation above to determine the exponentiation used.

Table 4, SYSCAL and dBZ0

Term	Units	Value	Radar Equation Value	dB	SYSCAL	dBZ0
2^10	Unitless	1024.00	1024.00	30.10	30.10	30.10
ln(2)	Unitless	0.693147	0.693147	-1.59	-1.59	-1.59
wavelength	cm	10	100	20.00	20.00	20.00
cm to m conversion	m	0.01	0.0001	-40.00	-40.00	-40.00
m3 to mm6/m3 conversion		1.00E+18	1.00E+18	180.00	180.00	180.00
milliwatts to W conversion	W	0.001	0.001	-30.00	-30.00	-30.00
km to m conversion	m	1000	1000000	60.00	60.00	60.00
Noise	mW			-78		-78
antenna gain^2	Unitless			-91.60	-91.60	-91.60
antenna beamwidth	degrees	0.91	0.8281	0.82	0.82	0.82
degrees to radians conversion	radians	0.017453	0.000305	35.16	35.16	35.16
Pulsewidth	Microseconds	1.57	1.57	-1.96	-1.96	-1.96
microseconds to seconds conversion	sec	0.000001	0.000001	60.00	60.00	60.00
speed of light	m/sec	3.00E+08	3.00E+08	-84.77	-84.77	-84.77
Refractivity^2	Unitless	0.93	0.93	-.315	.32	.32
pi	Unitless	3.14159	31.0062	-14.91	-14.91	-14.91
transmitted power	kW	700	700	-28.45	-28.45	-28.45
kW to W conversion	W	1000	1000	-30.00	-30.00	-30.00
transmitter waveguide loss	Unitless			2.25	2.25	2.25
receiver waveguide loss	Unitless			0.63	0.63	0.63
receiver detection loss	Unitless			1.5	1.5	.5
a^2g (legacy)	Unitless			-57.00	-57.00	
receiver gain (ORDA)	Unitless			-35.75		-35.75
Total					10.50	-47.25

The SYSCAL value 10.50 agrees well with the field measured SYSCAL of 10.627 (average SYSCAL from all field systems before installation of EMI Filter, standard deviation is 1.10).

The ORDA receiver gain is the gain from the Receiver Protector 2A3J1 to the input of the IFD, including the 2db insertion loss from Signet's anti-aliasing filter and a 3dB attenuator between the Mixer/Preamp and the IFD. This differs from legacy significantly because of removal of the IF and analog portions of the legacy receiver.

The effect of this is that ORDA's calibration constant, dBZ_0, differs from SYSCAL by the ORDA Receiver Noise value (around–78dBm), the difference in receiver gain (approximately 19dB), and the a^2 term (adds approximately 3dB to the receiver gain in the legacy WSR-88D).

Noise Power

The noise power of a receiver system determines the minimum discernible signal, and is therefore one of the prime characteristics of a receiver system. Since this noise power is not signal but is present in every receiver sample taken, it must be removed from the receiver return to accurately measure the signal power. Measurement of noise power is done periodically to ensure accuracy, and to detect receiver problems.

The noise power expected for the WSR-88D receiver in ORDA configuration depends on several factors:

- Receiver Bandwidth
- Receiver Noise Figure (computed from Receiver Noise Temperature)
- Antenna Temperature
- Transmission Loss from Feedhorn to Receiver Front End
- Ambient Temperature

Noise power is related to noise temperature by the following equation:

$$N = kTB$$

where:

Variable	Definition
N	Noise Power
k	Boltzmann's Constant, 1.38065×10^{-23} J/K
T	Noise Temperature in Kelvin
B	Receiver Bandwidth in Hertz

For WSR-88D, T is composed of 3 temperatures:

- T_A – Antenna Temperature, the Noise Temperature of the antenna into "blue sky" (i.e. no ground radiation affects) with additions by the atmosphere, side lobes, and the radome
- T_l – Transmission Loss, the Noise added by the waveguide from the feedhorn to the Receiver Front End
- T_R – Receiver Noise Temperature, the Noise added by the receiver system

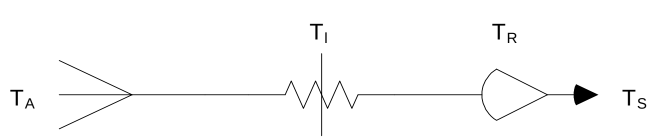


Figure 3, Noise Power

So Noise Power for WSR-88D becomes:

$$N = k\left(T_A + T_l + T_R\right)B$$

Therefore, nominal expected Noise Powers for WSR-88D with ORDA becomes:

Table 5, Expected Noise Power

Parameters	T_A	T_l	T_R	T_S	B (kHz)	N (dBm)
Short Pulse, Receiver Front End Dummy Loaded	290	0	250	540	600	-113.5
Short Pulse, Antenna	30	45	250	325	600	-115.7
Long Pulse, Receiver Front End Dummy Loaded	290	0	250	540	200	-118.3
Long Pulse, Antenna	30	45	250	325	200	-120.5

These estimates are the best Noise Powers we expect on the system, mostly because the value of "B", the noise bandwidth, is assumed to be identical to the signal bandwidth, and both of them are assumed to be perfect. In reality, the actual noise bandwidth will be larger, so actual system noises will measure slightly (estimated at 0.5dB) higher than this.

The Expected Noise Power in Table 5 is the noise power at the input to the antenna. Our typical reference point for Noise Power (and therefore Minimum Discernible Signal) is at the Receiver Front End, and therefore the Noise Power level needs to be changed by the loss from feedhorn to receiver front end. This loss is typically around -0.63dB, giving us an MDS at the receiver front end of approximately -114.5dBm for Short Pulse and -119.5dBm for Long Pulse with corrections for path and noise filter difference.

Variables

Wherein we take the separate parts of dBZ_0 and show the accuracy of those measurements. There are 2 considerations for each part: calibration accuracy and parameter drift. Calibration accuracy typically depends on the accuracy of the test equipment the technician uses. Parameter drift depends on ambient temperature, component age (for hardware related parameters), and voltage drift, et al. For this paper, both these parameters are considered together when we are calculating parameter accuracy.

Constants

These are the C constants above. There is no deviation for these variables.

Wavelength

Wavelength varies as the frequency changes. Its accuracy is tied to the accuracy of the RF Frequency Generator. The actual wavelength is never measured independently.

Pulsewidth

Pulsewidth is measured by the technician and input into adaptation data. Its calibration accuracy depends on the technician's measurement with an oscilloscope. The pulsewidth is measured at the -3dB point in voltage ($1/\sqrt{2}$ in power). Pulsewidth drift depends on the 3A5 Pulse Shaper's stability and the Klystron Filament Voltage during transmission.

Transmitter Power

Peak Transmitter power depends on the pulsewidth because of duty cycle, and is calibrated by the technician. Its accuracy depends on the pulsewidth, calibration of the power meter, and power meter drift.

However, the power calculated for dBZ_0 uses approximately 30 independent samples, practically eliminating errors from variance in a single power measurement.

Transmitter Path Loss

This path loss is from the klystron output to the feedhorn. Its accuracy depends on the accuracy of the technician's test equipment.

Duty Cycle

This calculation's accuracy depends on the accuracy of the pulsewidth measurement and the PRT accuracy.

Power Meter

The power meter's accuracy depends on the resolution of the meter used, technician calibration, and thermal drift.

I_0

I_0 is the measurement of 0dB S/N at the receiver front end, also called Minimum Discernible Signal (MDS). It therefore is the combination of Noise and receiver gain.

Noise

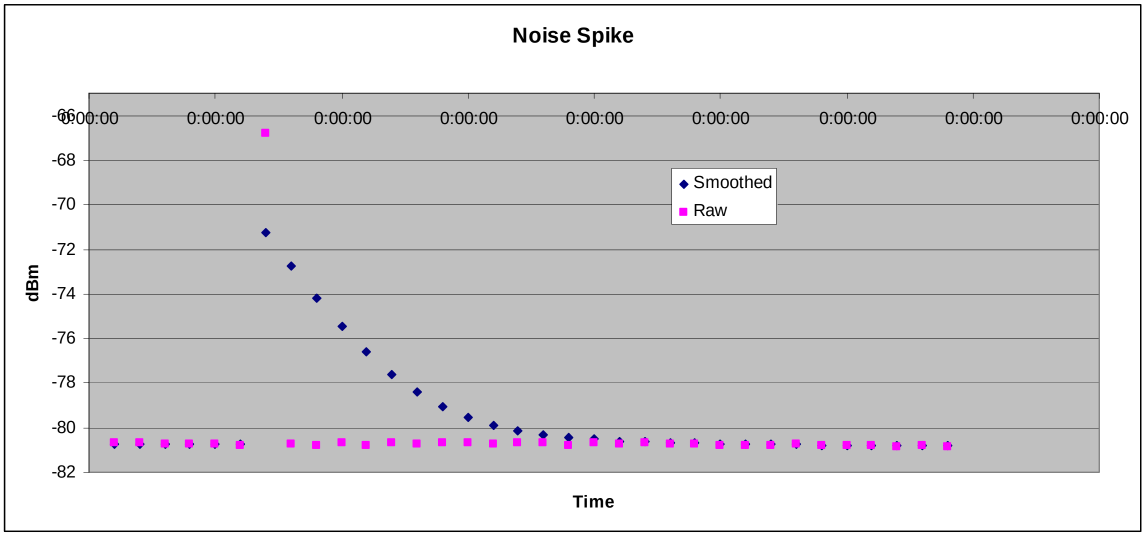
Noise is measured by the system. Its accuracy depends on the accuracy of the IFD and the number of samples we measure. . For ORDA, we use at least 3000 samples for each noise measurement. Also, the noise measured is smoothed so single anomalies don't have an inordinate affect. The smoothing is done on the results of each noise measurement, using a simple 2 pole IIR (Infinite Impulse Response) filter. The equation for Smoothing is:

$N = N_C(S) + N_O(1-S)$, where:

N	Smoothed Noise in Watts
N_C	Current Noise Measurement
N_O	Previous Smoothed Noise value
S	Smoothing factor from 0 to 1, typically 0.33

This works extremely well smoothing small variations in noise. However, a large noise spike (greater than 1dB) will cause this filter to take several calibrations to settle; the larger the spike, the longer the settling. A 10dB noise spike can cause the noise measurement to be more than 1dB in error for up to 7 calibrations after the spike (see Table 6 for an example from KJIM). Since noise spikes over 1dB are uncommon, this problem is not seen routinely in the field.

Table 6, Noise Spike



Receiver Gain

The receiver gain is measured each calibration, and its accuracy depends on the manual calibration done by the technician on the critical path, and the accuracy of the calibration of the 7-Bit Test Attenuator. During the calibration we take 10 measurements at different power levels and measure the gain of each, thus reducing variance from a single measurement.

Detection Loss

This loss is from the matched filter. Matched filtering is done in software with a digital matched filter. The filter loss can be calculated accurately, and the filter's transition is much steeper than an analog filter, with better phase characteristics.

Water Refractivity

This constant is in adaptation data in the event water changes its refractivity.

Antenna

Antenna parameters depend on antenna geometry and radiated frequency. Since the Antenna gain includes the losses from support structures and the radome, its accuracy also depends on those losses.

Gain

Accuracy depends on sun flux measurements in Sun Check calibration.[iii] This gain measurement includes affects from support structures and the radome, along with changes in the path from the feedhorn to the receiver front end.

Beamwidth

This parameter depends on frequency and deterministic characteristics of the antenna. It is measured during off line calibration in Sun Check, using the known angular displacement of the sun. The measurement is displayed, but the beamwidth in Adaptation Data is not updated; it is for information only.

Waveguide Loss

This is the loss from the path from the feedhorn to the receiver front end. These losses are in adaptation data, and are assumed to be constant. Variations in these losses are detected in Sun Check calibration and added to the Antenna Gain.

Atmospheric Loss

This is treated as a constant, based on elevation angle. The constant is in Adaptation Data for each range of angles. Atmospheric loss actually depends on altitude, air density, water vapor, and other factors, so our atmospheric loss constant for elevation angle is more accurate at longer ranges. The constants chosen per angle are to minimize the errors for that angle.

Range

Range accuracy depends on the clock accuracy. ORDA uses a much more accurate clock than legacy (higher crystal frequency), and the clock is not derived from the COHO.

Accuracy

The overall accuracy of reflectivity depends on the accuracy of all the components of the radar equation. For the ORDA, the radar equation looks like:

$$dBZ = 10\log\left(\frac{P_r - N}{N}\right) + dBZ_0 + 20\log(R) + aR$$

Table 7, Reflectivity Accuracy

Term	Standard Deviation (dB)i	Description
λ^2	0.00008	Wavelength, part of dBZ_0
R	0.00004	
P_t	0.108	Transmitter Power, part of dBZ_0
G^2	0.44iii	Antenna Gain, part of dBZ_0
θ^2	0.26	Beamwidth, part of dBZ_0
L	0.1	Receiver Losses, part of dBZ_0
L_D	0.05	Detection Loss, part of dBZ_0
I_0	0.05	0dB S/N, part of dBZ_0
Total σ	**0.5363**	

Any terms not included in Table 7 are 0 (for example, "a" is a constant, and therefore has no Standard Deviation).

Measurements

Reflectivity Calibrations Measurements

These measurements were made on the WSR-88D, and show the stability of our automatic calibrations. The actual test for each parameter is discussed below.

Noise

Receiver Noise is always measured above 3.5 degrees to reduce affects from ground noise. The noise values are corrected for ground noise based on elevation when given to the Signal Processor. The noise level expected by the Receiver is the Noise Power from Table 5 plus the Receiver Gain from Receiver Front End to IFD (approximately 34dB).

Table 8, Measured Noise

Site	Short Pulse		Long Pulse	
	Noise (dBm)	St Dev (dB)	Noise (dBm)	St Dev (dB)
KCRI ch 2	-80.15	0.026	-84.60	0.080
KJIM Dummy Load	-80.69	0.033		
KREX Dummy Load	-80.24	0.039		
KCRI ch 1				
KVNX	-80.02	0.271		

I_0

The 0dB S/N of the receiver referenced to the receiver front end. This is also known as system MDS. The slope from calibration is essential to the I_0 calibration. The Y-Intercept information from calibration gives us additional stability information.

For a perfect calibration, the slope would be 1.00 and the Y Intercept would be 0.0. Linearity stability is key to getting a consistent Inaught needed for a good dBZnaught.

As Table 9 clearly shows, the calibration calculation of the linear characteristics of the receiver transfer curve is consistent and stable.

Table 9, Linearity Equation

Site	Slope		Y Intercept	
	Value	St Dev (dB)	Value	St Dev (dB)
KCRI ch 2	1.005	0.00083	0.1501	0.032
KJIM	1.00	0.000734	-.08	0.024
KREX	1.003	0.000795	0.0788	0.021
KCRI ch 1				
KVNX	0.996	0.00394	-0.106	0.096

Table 10, Inaught

Site	Short Pulse		Long Pulse	
	I_0 (dBm)	St Dev (dB)	I_0 (dBm)	St Dev (dB)
KCRI ch 2	-114.16	0.07	-119.17	0.22
KJIM	-112.35	0.116		
KREX	-111.75	0.097		
KCRI ch 1				
KVNX	-114.27	0.245		

Transmitter Power

Peak power measured during the surveillance cut.

Antenna Gain

Antenna Gain is calculated based on frequency and deterministic antenna characteristics and then calibrated using sun flux.

dBZ_0

Combines all the previous elements, making the reflectivity radar equation depend dynamically only on receive power, range, and atmospheric losses. During operation, dBZ_0 is recalculated at the end of every VCP. While not operating, it is calculated periodically to detect problems.

Since Power varies more than Inaught, we expect dBZ_0 to show a higher standard deviation than Inaught, and it does. KVNX shows a higher standard deviation mostly because there are very few samples.

Site	Short Pulse		Long Pulse	
	dBZ_0 (dBZ)	St Dev (dB)	dBZ_0 (dBZ)	St Dev (dB)
KCRI ch 2	-47.47	0.198	-57.68	0.21
KJIM	-45.20	0.120		
KREX	-46.38	0.151		
KCRI ch 1				
KVNX	-48.17	0.305		

Dynamic Range

For the WSR-88D Dynamic Range is defined as the range from MDS (I_0) to 1dB compression of the signal. Our IFD is the limiting factor for compression. We are required to produce at least 93dB of dynamic range. The MDS point calculated is not actually the smallest signal we can reliably see, it is defined as 0dB S/N for ease of measurement. Realistically, we can easily see returns to at least –5dB S/N, translating to a signal + Noise approximately 1dB above Noise.

Off-Line Calibrations

The technician uses these calibrations to verify and correct the constants used for dBZ_0. The algorithms described are simplified from the actual algorithms used.[iv]

Sun Check

- Purpose
  - Accurate position of the sun, uses noise of sun and internal noise source to calibrate antenna/radome gain
- Description
  - 2 Parts
    - Positional Accuracy
      - Raster scan across sun, parabolic curve fit for exact location
      - Antenna must be within .3° to find sun
      - This part also measures the beamwidth of the antenna
    - Gain Check

            - Sun Flux is input and corrected for sun diameter, distance, and other factors to get an Expected Sun Noise Temperature
            - Noise measurements are taken pointed away from the sun and pointed directly at the sun, using the internal calibrated noise source, to measure Sun Noise Temperature
            - The ratio of these 2 values results in the actual antenna gain value

Short or Long Pulse Reflectivity Error Estimate

- Purpose
    - Estimates the errors in dBZ_0 related to power, noise, calibration linearity, and path, the dBZ_0 variables that change most pulse to pulse.
    - Allows a technician to quickly isolate problems in dBZ_0 measurements (high delta dBZ_0's)
- Description
    - 5 iterations of:
        - Noise
        - Reflectivity and Linearity
            - Need I_0 from this
    - Take out worst of each measurement (Noise, I_0 (shared path))
    - Average the remaining 4 measurements
    - Power Measurement
        - 8 second warm up
        - measure power once per second for 10 seconds
        - Throw out min and max power measurement
        - Average the 8 power readings left
        - Calculate peak power
    - Compare to expected's
        - Peak Power = 700Kw Transmitter
        - Noise = Adaptation Data
        - Shared Path = Adaptation Data for shared receiver channel, from receiver Front End to IFD input
        - I_0 (shared path) = Shared Path + 0dB S/N estimated
        - DBZ_0 = Adaptation Data
    - Show all data, give error estimate for each parameter

Full Linearity

- Purpose
    - Uses the test attenuator and both injection points to map the entire receiver transfer curve.
    - Calculates MDS, Dynamic Range, and DBZ_0
    - This test should show degradations in the receiver, and give the technician a good idea of where to start looking for receiver problems.
    - This test uses some alternate means to determine some basic system characteristics to help verify system consistency
- Description
    - Run Noise
    - Run Dynamic Range
    - Run library routine for Full Linearity
    - From the data received:
        - If no Low Level CW Interference (determined in Full Linearity)
            - Display MDS, Dynamic Range
    - Calculate MDS, DYN Range, and dBZ_0

    - Display receiver transfer curve graphically
    - Display measured and calculated data

Noise

- Purpose
    - Measures the system blue sky noise in short pulse or long pulse
    - This test is to calibrate the Noise level for use on line. It allows the technician to sample the noise multiple times to reduce variance, and then update the noise level in adaptation data.
    - This is done separately for short pulse and long pulse
- Algorithm
    - Park the Antenna
    - Do not run routine if antenna below 5° elevation
        - An override is available to get noise levels from any elevation or azimuth angle
    - Select pulse width
    - Select iterations
        - Default of 5
        - Selectable from 1 to 99
    - Run the library routine for Noise
    - Display the average for all iterations, and the standard deviation

Noise Temperature

- Purpose
    - Uses a calibrated Noise Source to determine the receiver Noise Temperature
    - This routine verifies the Noise Temperature and allows the technician to see stability problems with the receiver.
    - Noise Temperature is extremely sensitive to receiver changes and helps early detection of receiver problems.
- Algorithm
    - Park antenna
    - Switch to pulse width desired
    - Provide a selection for iterations of Noise desired
        - Default is 5
        - From 1 to 99 times
    - Run Noise Temperature routine selected times
    - Display results with standard deviation

KD

- Purpose
    - The KD (Klystron Delayed) pulse is a delayed sample of the transmitter burst pulse, and has some desirable characteristics as a test source:
        - Phase coherent with transmitted pulse
        - Same shape as transmitted pulse
    - Times the KD pulse for reference with Clutter Suppression, compares FE and CAB injection points. Measures Receiver Protector isolation
    - This test is for technician troubleshooting
- Algorithm
    - Show Parameters

- Switch to KD pulse mode mode (25m samples vs 250m samples, so the pulse center can be found)
- Radiate for 8 seconds to warm up the transmitter
- Search for the center of the KD pulse
- Switch between Front End and Cabinet Injection, gather data
- Switch between Receiver Protect forced on and Receiver Protect in normal, gather data
- Display results for the technician

Clutter Suppression

- Purpose
  - Measures the Reflectivity clutter suppression of an "ideal" clutter target, the KD pulse
  - This test is for technician troubleshooting
  - A poor result in Clutter Suppression typically indicates transmitter stability problems
- Algorithm
  - Show Parameters
  - Switch to KD pulse mode (25m samples vs 250m samples, so the pulse center can be found)
  - Radiate for 8 seconds to warm up the transmitter
  - Use the pulse center determined in KD
  - Gather data from signal processor on signal strength with no clutter filtering and with clutter filtering.
  - Display results for the technician

RFD

- Purpose
  - Check the RF Drive Pulse for amplitude/phase
  - This test is for technician troubleshooting
- Algorithm
  - Generate RF Drive test pulses and measure them. We need to use a very narrow range (i.e. 25m instead of 250m) to ensure we get the center of the pulse since we can't vary the sample timing
  - Calculate expected RFD magnitude, compare to actual
  - RFD phase and jitter
    - Gather 128 points of IQ data
    - For nn=1 to 128
      - $Phase(nn) = \tan^{-1}\left(\frac{I_{nn}}{Q_{nn}}\right)$
      - $RFD\_phase(nn) = Phase(nn) - Phase(nn-1)$
    - $RFD\_avg\_phase = \frac{\sum_{m=1}^{128} RFD\_phase(m)}{128}$
  - RFD_phase_jitter= Standard Deviation of RFD_Phase
  - KD Pulse
    - Radiate for 8 seconds
    - Gather 128 points of IQ data

- For nn=1 to 128
  - $Phase(nn) = \tan^{-1}\left(\frac{I_{nn}}{Q_{nn}}\right)$
  - $KD\_phase(nn) = Phase(nn) - Phase(nn-1)$
- $KD\_avg\_phase = \frac{\sum_{m=1}^{128} KD\_phase(m)}{128}$

- KD_phase_jitter= Standard Deviation of KD_Phase
- Display
  - Phase Jitter of KD should be larger than RFD
  - Phase difference should be fixed

CW Substitution

- Purpose
  - Uses known input powers from an external Signal Generator to verify receiver power measurements.
  - This is an excellent, quick check of path calibration accuracy.
- Algorithm
  - Run the Reflectivity and Linearity calibration
    - We need $Noise_{Current}$, I_0 and FE_Shared
  - Have the technician hook up a calibrated CW RF signal to 4J16
  - Read the Power at the IFD
    - CW_{TESTIN}
  - Have the technician hook up a calibrated CW RF Signal to 4J15
  - Read the Power at the IFD
    - $CW_{TESTOUT}$
  - Have the technician remove the Signal Generator and test for removal and proper reconnection
  - Add Adaptation data for the critical path from 4J16 to FE Injection (R69+R72) to determine injected power
  - Use Adaptation data to determine the expected power measured from each signal
  - Compare Measured to Expected
    - $CAB_{error} = J15_{exp} - CW_{TESTOUT}$
    - $FE_{error} = (J16_{exp} - CAB_{error}) - CW_{TESTIN}$
    - $TestPath_{error} = (FE\_shared - FE_{error} - Cab_{error}) - FE\_Shared\_Calc$

Test Attenuator

- Purpose
  - This test calibrates all the steps of the test attenuator and lets the technician update Adaptation Data with the new calibration
  - We use Long Pulse to get the advantage of lower noise, so we have more usable points on the test attenuator
  - Since the Test Attenuator is used for the samples to calculate the receiver transfer curve and thus I_0, its calibration is essential to an accurate dBZ_0.
  - Since steps above 80dB attenuation are not used in on-line calibration, they are set to ideal if they are out of tolerance. These low level signals are subject to fluctuation due to any type of CW interference, especially that caused by the RF Generator.
- Algorithm

- We cannot get linear results from all 104 steps using just one injection point, therefore we must get data from both injection points and correlate them
- We correct samples for noise
- This test uses the 0dB attenuation input into the Cabinet as a reference for all other tests since this power level is below 1dB compression and only has the insertion loss of the test attenuator (it's closest to ideal).
- It then refers the 0dB Cabinet point to the 32dB Front End Point
- The system measures the power from the Front End (FE) Path and the Cabinet (CAB) Path for every attenuation step.
- We check to see if there's low level CW interference in our data
- Using the references, we calculate the expected power at each attenuation for FE and CAB.
- We determine the error between the expected and measured data at each attenuation.
  - Values above saturation and "in the noise" are not used.
- The technician views the new calibration and decides whether to accept it into Adaptation Data.

Velocity/Spectrum Width Processing

- Purpose
  - Inputs known I and Q samples into the RVP to measure V and W throughout the Nyquist Interval.
  - This test verifies proper velocity and spectrum width calculations in the RVP.
  - This test helps split the system for technician troubleshooting of velocity/spectrum width problems.
- Algorithm
  - Run library routine for V/SW Processing
  - Display V and W expected and measured for every different V and W in the file
  - Highlight if any values are out of tolerance.

Velocity/Spectrum Width

- Purpose
  - Measures the receiver system capability to measure V and W at 4 selected Nyquist intervals.
  - This test puts phase shifted CW through the entire receiver path.
- Algorithm
  - Run Library routine for V/SW
  - Display V and W expected and measured for each V and W input
  - Highlight any values out of range

Transmitter Power

- Purpose
  - Calibrates the Power Monitor to match known transmitter power output
  - Transmitter Power is one of the variables determining dBZ_0.
- Algorithm
  - The technician verifies the transmitter power measurement off-line
  - Radiate transmitter for 8 second warmup
  - Measure transmitter power for 30 seconds, once per second
  - Throw out high and low readings
  - Average all readings
  - Correct for path to transmitter output
  - Correct for duty cycle

- Compare to calibrated peak power
- Use ratio to correct adaptation data

RF Test Switch

- Purpose
  - Calibrates 4A29 Log Amp Detector for RF testing (RIOS)
  - This is solely used for Off Line testing of the receiver
- Algorithm
  - This procedure checks the transfer curve of the 4A29, and also corrects for bias.
  - Turn on CW test signal, have technician measure power at input to 4A29
  - Use 5 samples at either end of linear transfer curve (5 samples from 0-4dB attenuation and 5 samples from -36 to -40 dB attenuation) to calculate the curve (Least Squares Linear Curve Fit).
  - Display results and allow technician to update adaptation data for 4A29

Conclusion

Due to the similarity between legacy and ORDA, both systems provide the same accuracy for dBZ measurements. Antenna uncertainties dominate dBZ accuracy, and cannot be trivially reduced.

Appendices

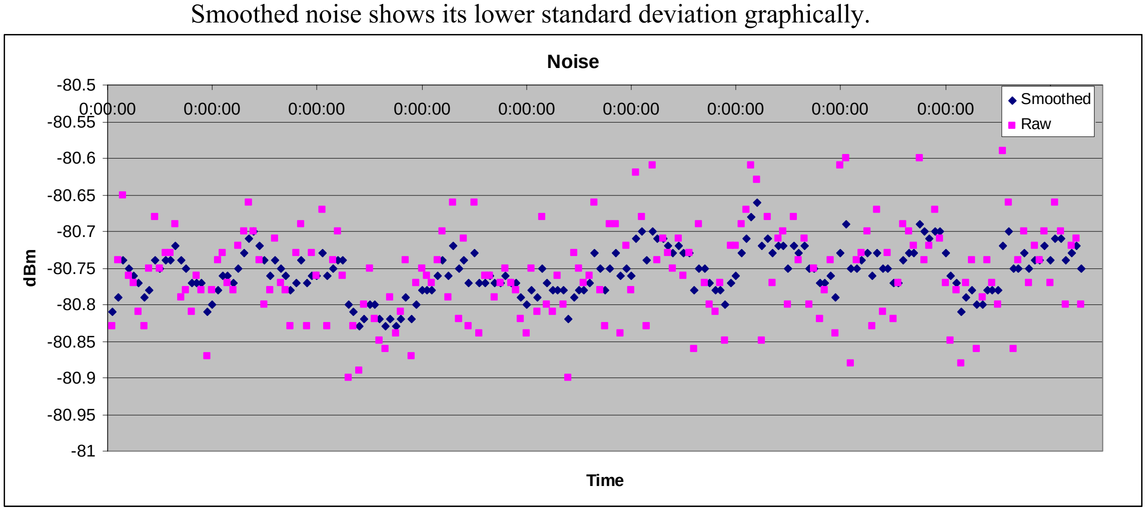
The appendices include calibration data from separate sites used in this report.

KJIM

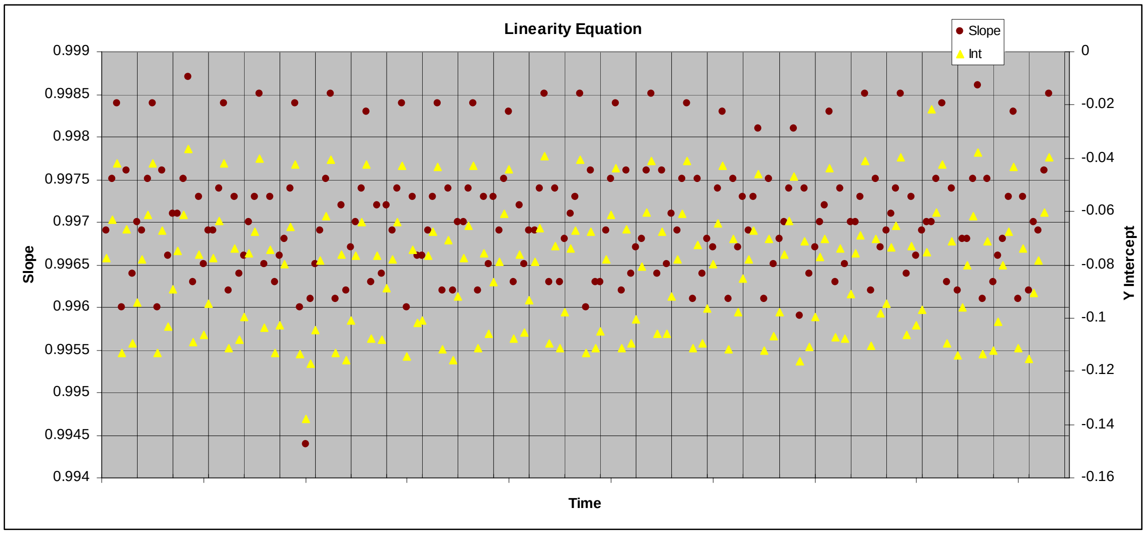
The following data for KJIM was taken on Dummy Load.

Noise/Linearity

Smoothed noise shows its lower standard deviation graphically.

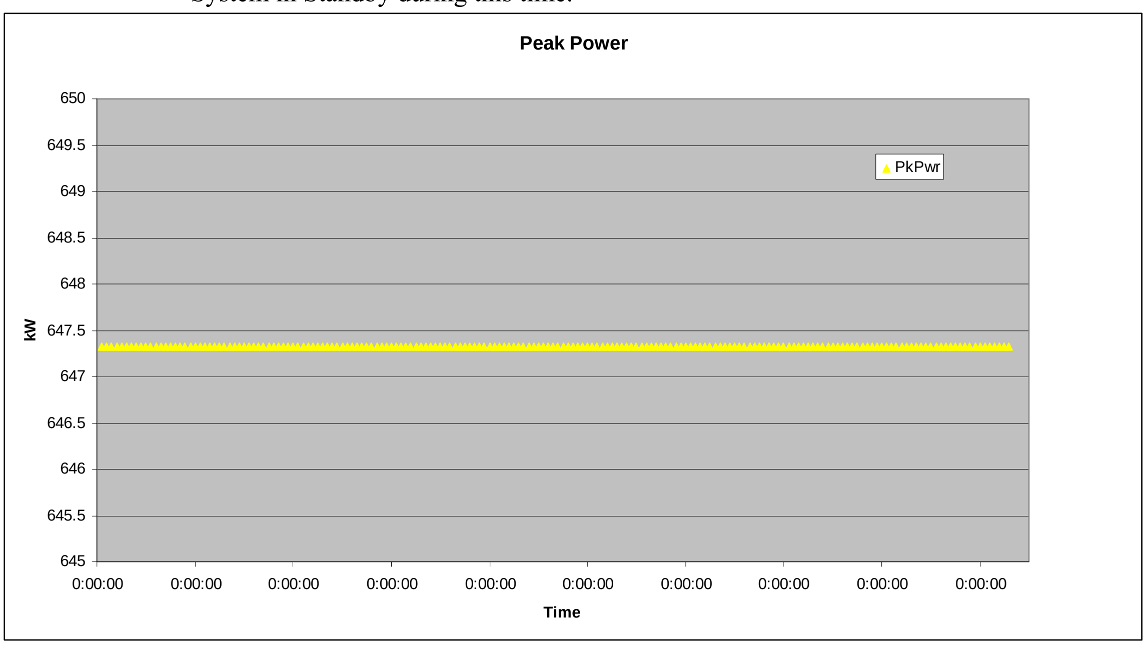


The periodicity of the calibration's linear equation is due to minute variations in the test attenuator. Since the calibration uses a sliding set of 10 points that repeats every 7 calibrations, differences in the test attenuator become obvious. Contributing to the ability to see this fluctuation is the stability of the calibration tests; we get the same results for every set of data.

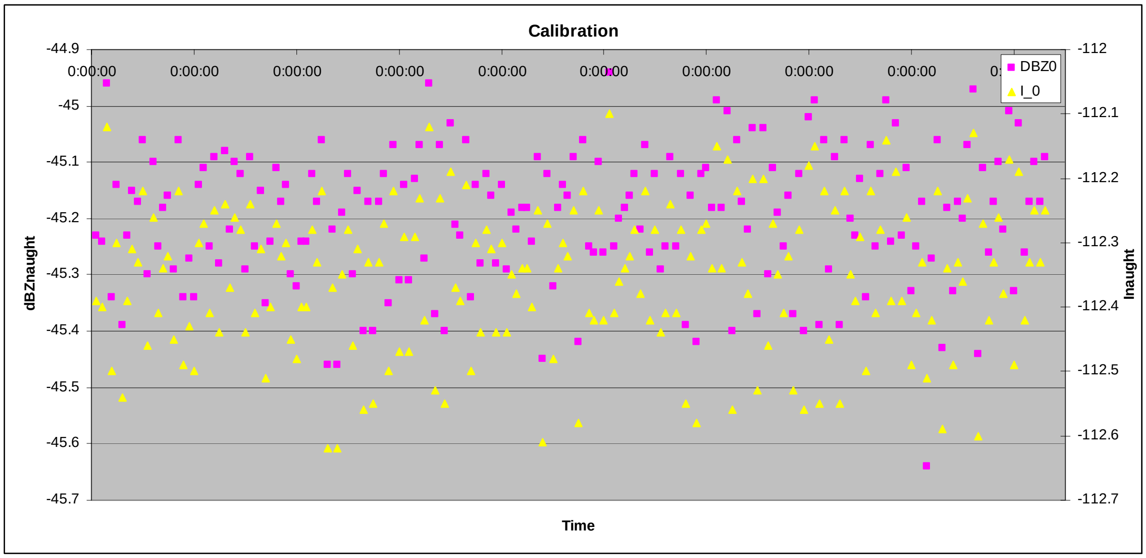


Transmitter Power

System in Standby during this time.



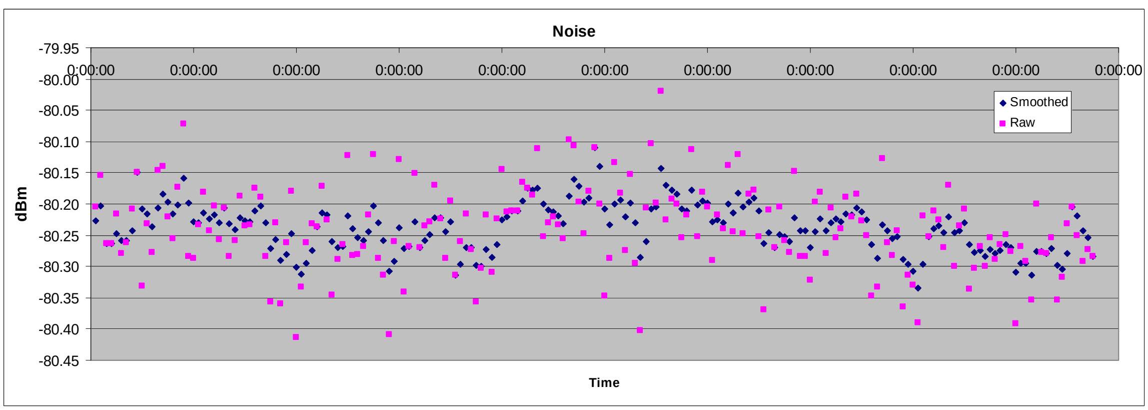
Inaught/dBZnaught

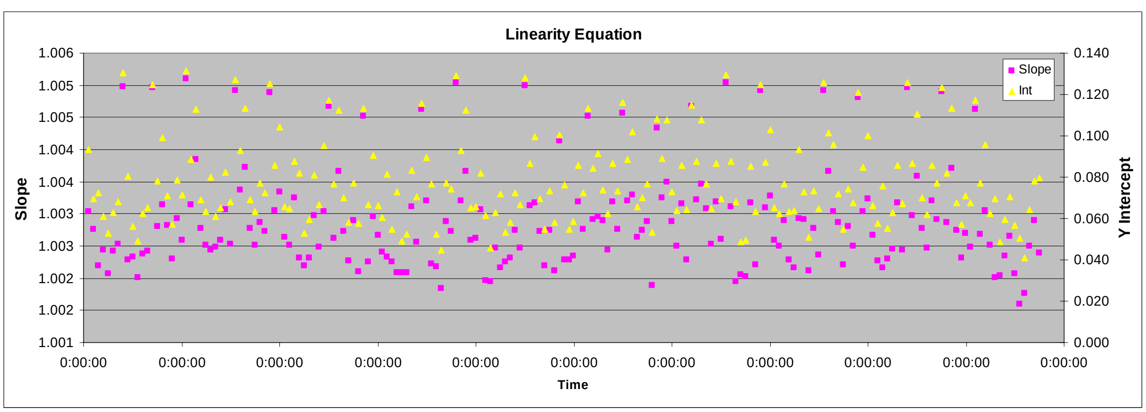


KREX

KREX is a test bed with no Antenna, therefore the receiver is always connected to a dummy load.

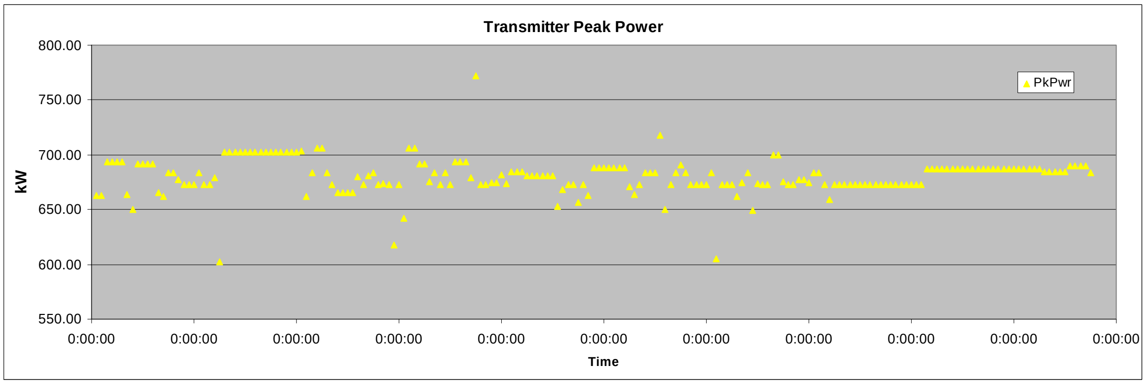
Noise/Linearity



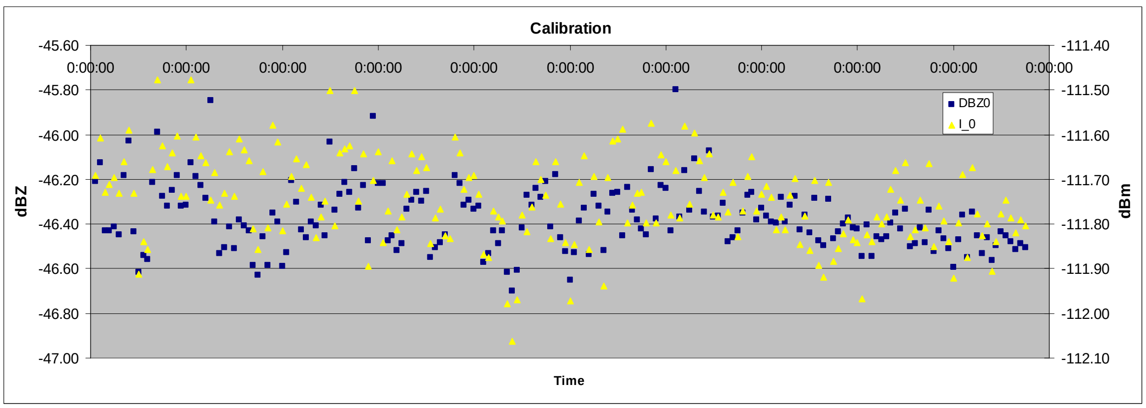


Transmitter Power

System in Standby part of the time (where power is the same on consecutive samples).



Inaught/dBZnaught



KCRI ch1

We do not have current calibration data for KCRI channel 1

Noise/Linearity

Noise levels
Slope
Y-intercept

Transmitter Power

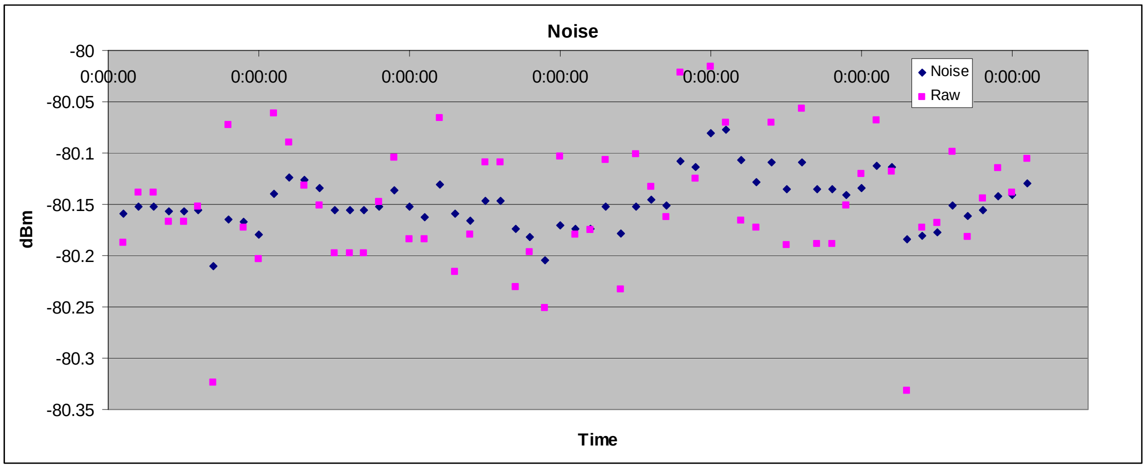
Peak Power measured by avg meter/burst pulse

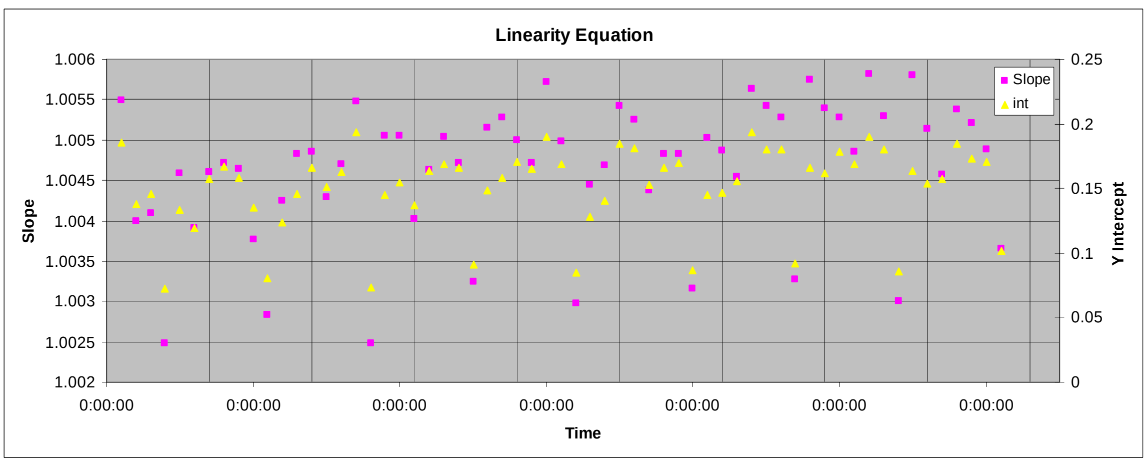
Inaught/dBZnaught

chart

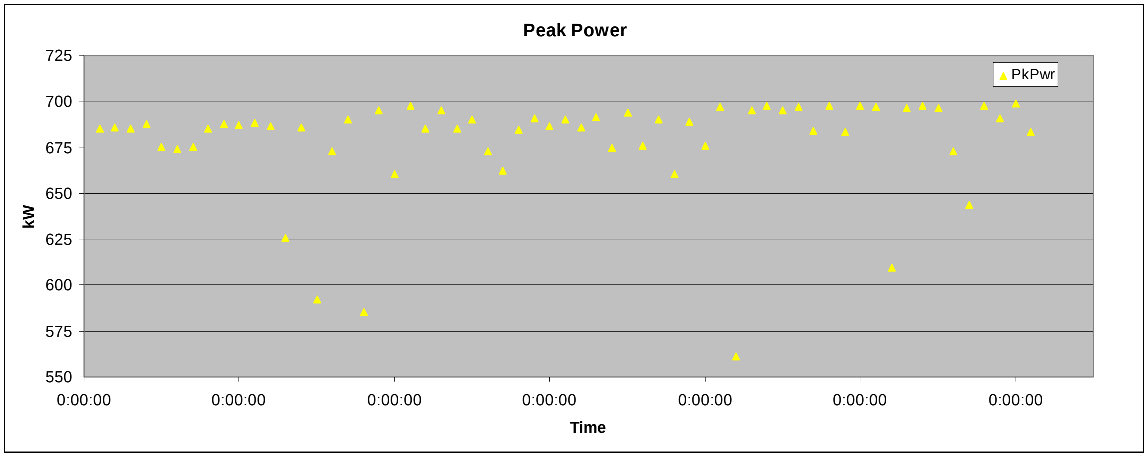
KCRI ch2

Noise/Linearity

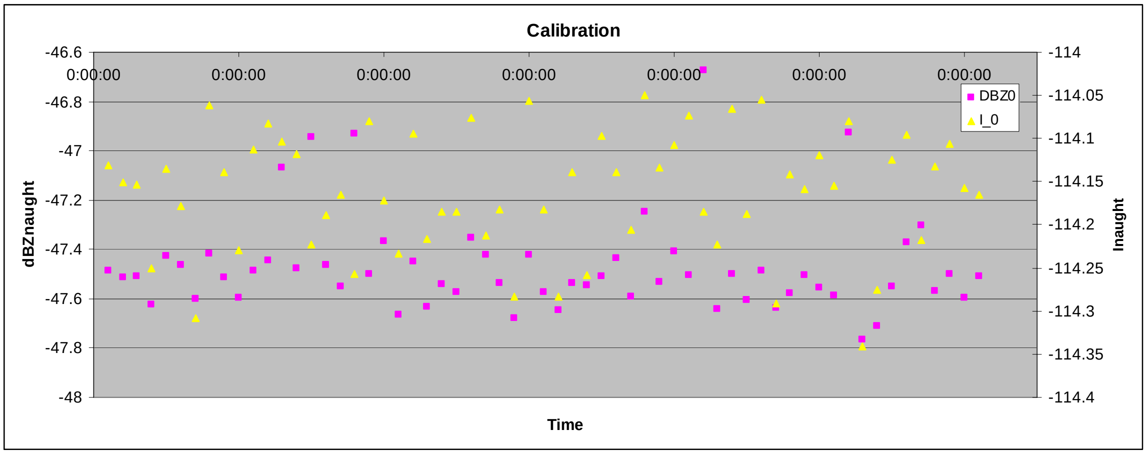




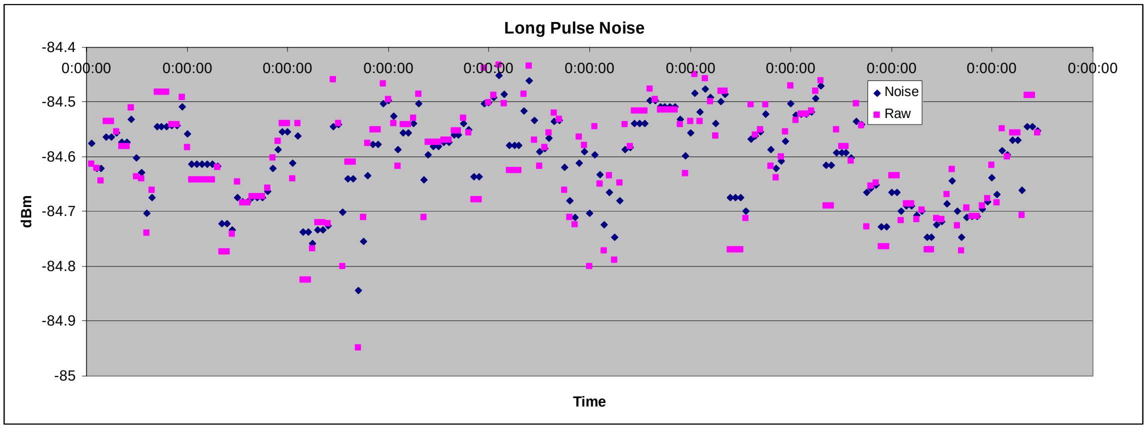
Transmitter Power



Inaught/dBZnaught

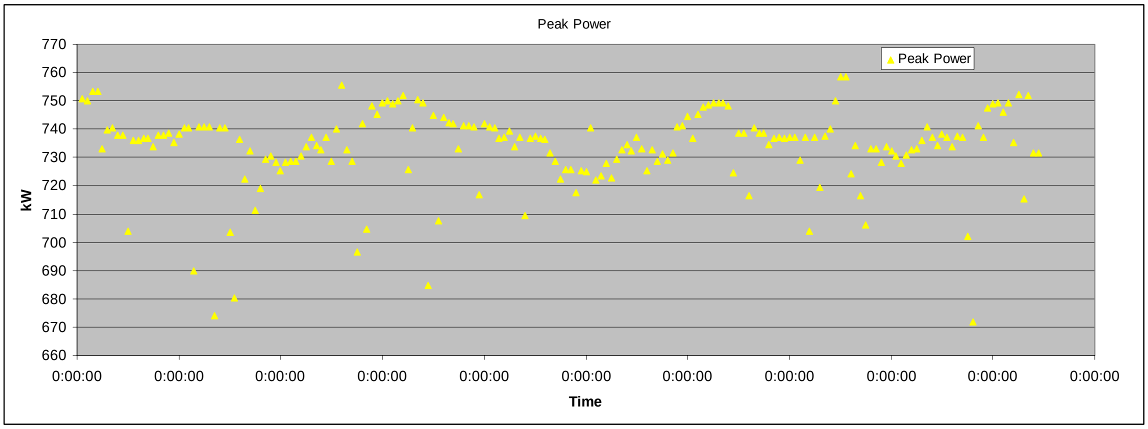


Long Pulse: Noise/Linearity

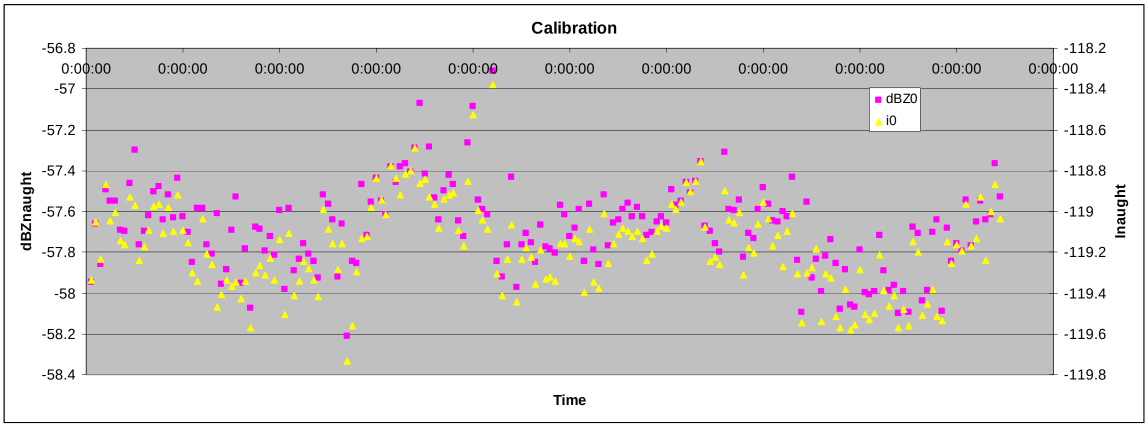


There is no Linearity Equation data for this data set.

Long Pulse: Peak Power

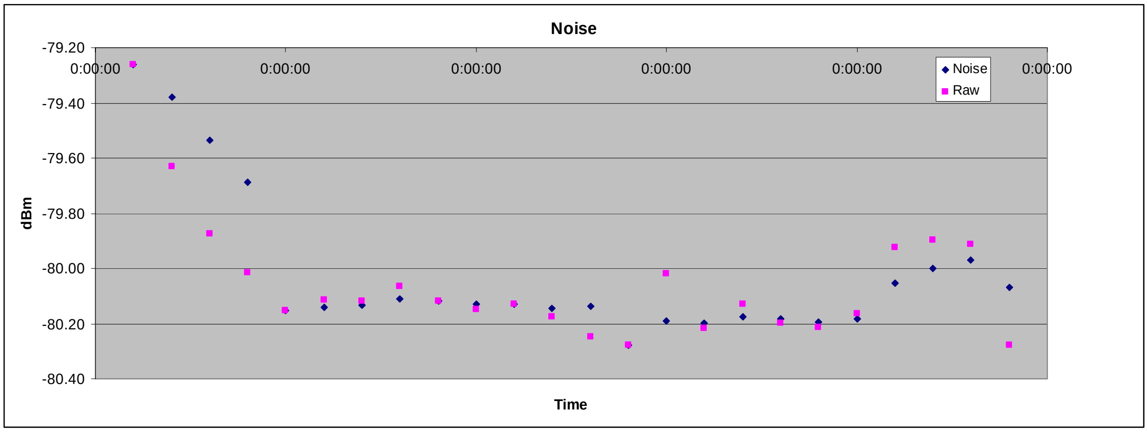


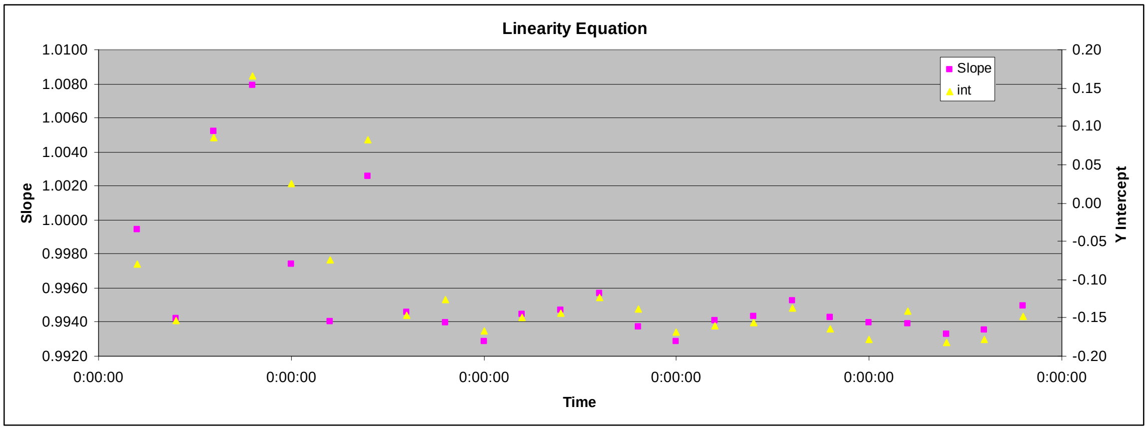
Long Pulse: Inaught/dBZnaught



KVNX

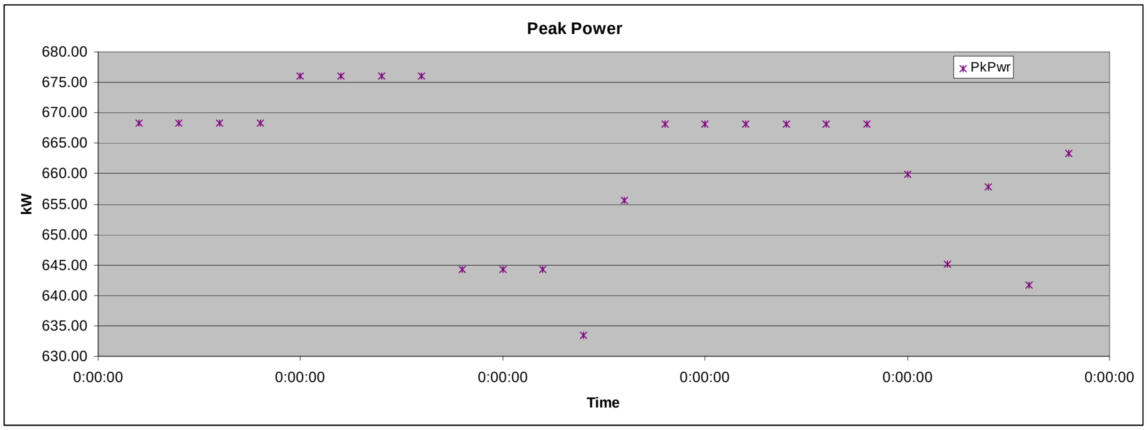
Noise/Linearity





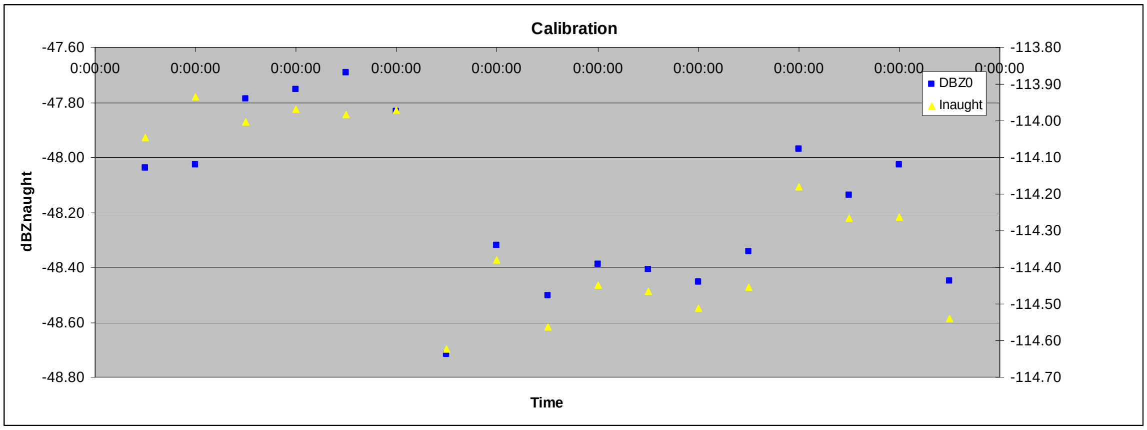
Transmitter Power

System in Standby part of the time (where power is the same on consecutive samples).



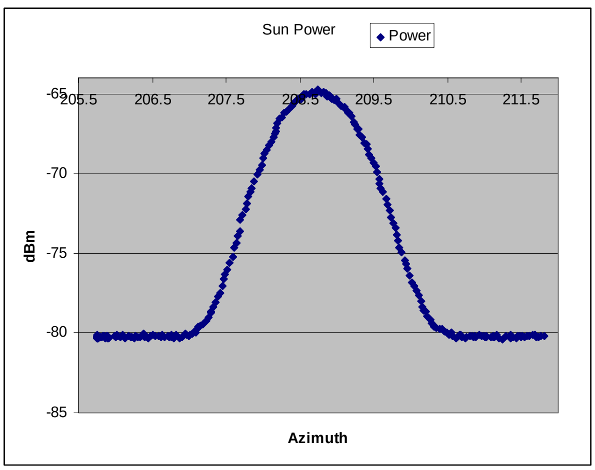
Inaught/dBZnaught

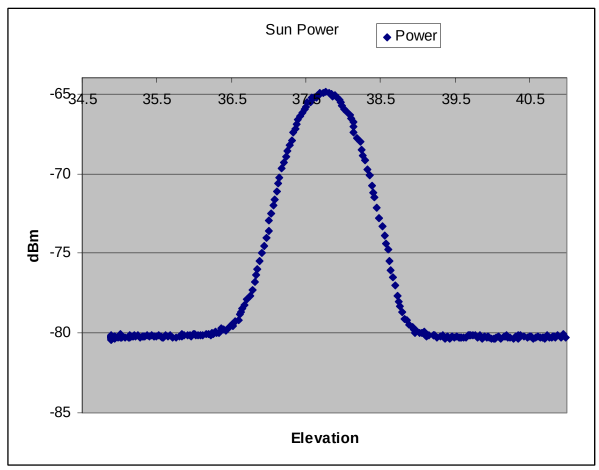
There are fewer samples here because the first 8 calibrations had the wrong adaptation data, thus invalidating that data. The wrong adaptation data did not affect the other measurements.



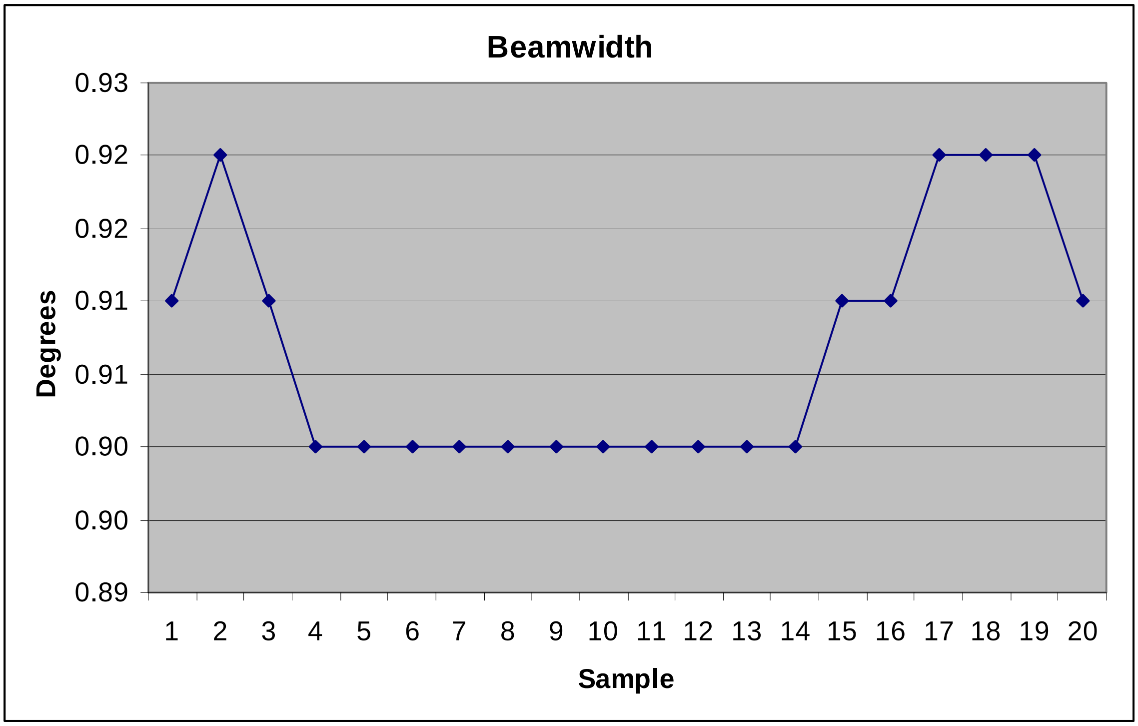
Suncheck

Az/El Position

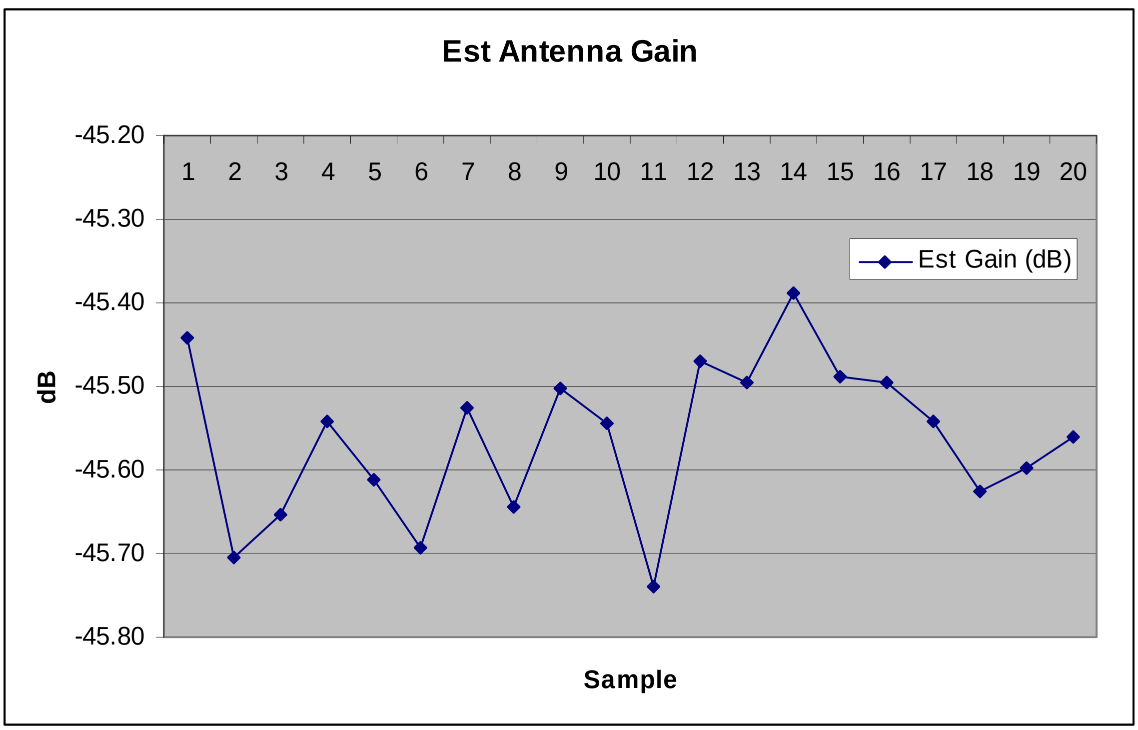




Beamwidth calculations are very consistent, and match well with expected beamwidth.
All this data taken on KCRI.



All this Antenna Gain data was taken on KCRI Ch1 and KCRI Ch2. The data was taken at different times on different days with different Solar Fluxes.



[i] "Calibration of the WSR-88D", Operational Support Facility, September 30, 1992
[ii] "RVP8 Manual", SIGMET, June 30, 2004

[iii] "On Measuring WSR-88D Antenna Gain Using Solar Flux", Dale Sirmans and William Urell, Radar Operational Center, January 3, 2001

[iv] "Off-Line Calibrations", ORDA Systems Engineering, August 18, 2004